GA-A25483

THERMAL STRESS ANALYSIS OF 1 MW GYROTRON COLLECTOR

by
C.B. BAXI, R.W. CALLIS, I.A. GORELOV, and J. LOHR

JUNE 2006

GENERAL ATOMICS

GA-A25483

THERMAL STRESS ANALYSIS OF 1 MW GYROTRON COLLECTOR

by
C.B. BAXI, R.W. CALLIS, I.A. GORELOV, and J. LOHR

This is a preprint of a summary paper to be presented at the 24th Symposium on Fusion Technology, September 11–15, 2006, Warsaw, Poland, and to be published in *Fusion Engineering and Design.*

Work supported by
the U.S. Department of Energy
under DE-FC02-04ER54698

GENERAL ATOMICS PROJECT 30200
JUNE 2006

ABSTRACT

During 2004 and 2005, collectors on three of the gyrotrons used at DIII-D failed due to stress cracks. In order to investigate reasons for these failures, a nonlinear elastic plastic thermal stress analysis of the collector/design was undertaken. The thermal stress analysis results indicated that the effective strain for oxygen free high conductivity copper material under the operating conditions limited the cycle life of the collector due to fatigue, resulting in failures.

The desired service life of more than 10^5 thermal cycles can be obtained by: 1) operational changes, such as increasing the frequency and amplitude of sweeping to reduce the effective heat flux, 2) design changes, such as: increasing the height and/or diameter of collector, enhancing the heat transfer coefficient by roughening the coolant channel walls, or 3) changing the material of the collector to dispersion strengthened copper such as Glidcop. The analysis and conclusions are presented.

I. INTRODUCTION

At the DIII-D tokamak, up to six gyrotrons supply electron cyclotron heating (ECH) power to the plasma. Each gyrotron injects up to 800 kW power for up to 5 s into the tokamak during operation and is designed to generate 1 MW for 10 s pulse lengths. A power of ~2000 kW is absorbed by the collector of each gyrotron from the electron beam. The present analysis was done to investigate the causes for collector failure and to find design and operational solutions to increase the life to more than 100,000 cycles.

The gyrotrons are manufactured by Communications and Power Industries (CPI). The collectors (Fig. 1) are 0.60 m diameter cylinders, 0.60 m in height. The material is oxygen free high conductivity copper (OFHC) and the collectors are cooled by water flowing through coolant holes in the wall at a design flow rate of 300 gpm. In order to reduce the peak thermal load on the collector walls, the beam is swept over the collector wall at 4 Hz using an external coil. Sweeping reduces the effective peak heat flux. Due to symmetry, only one flow channel was modeled to perform a 3D elastic plastic thermal stress analysis. The finite element code COSMOS [1] was used for the analysis.

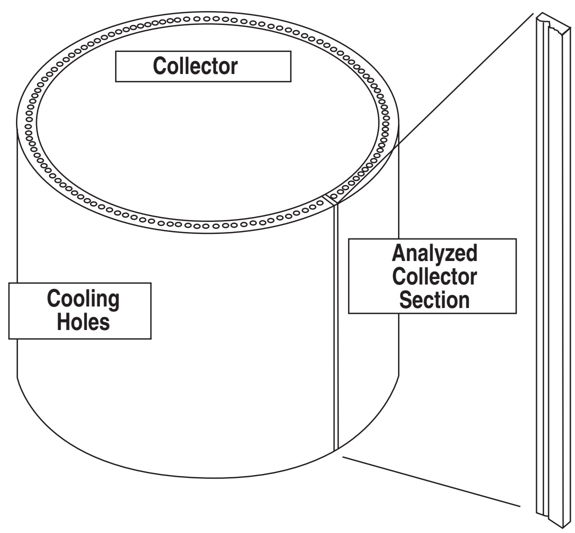

Fig. 1. The collector model.

II. THERMAL STRESS ANALYSIS

First, an analysis was performed for a stationary heat flux distribution to verify the method and assumptions. The results for such an analysis were available from CPI [2]. The heat flux profile was approximately triangular with a 20 cm base and a peak heat flux of 580 $\mathrm{W/cm^2}$. In order to perform the analysis, stress-strain curves (Fig. 2) as a function of temperature from Ref. [3] and fatigue life values (Fig. 3) for OFHC from Ref. [4] were used. The heat transfer coefficient was calculated as a function of local wall temperature by correlations described in Ref. [5]. These correlations take into consideration the temperature dependence of the heat transfer coefficient, the temperature for incipient boiling, and sub-cooled nucleate boiling in forced convection. It was also verified that the maximum heat flux on the coolant wall is much less than the critical heat flux. Comparison of this analysis with CPI analysis shows an excellent agreement, which is summarized in Table I.

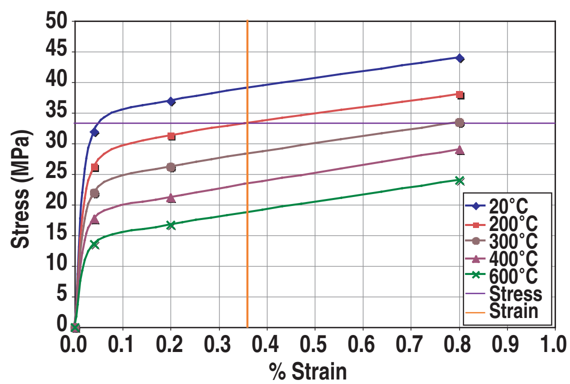

Fig. 2. Stress-strain curve for OFHC copper.

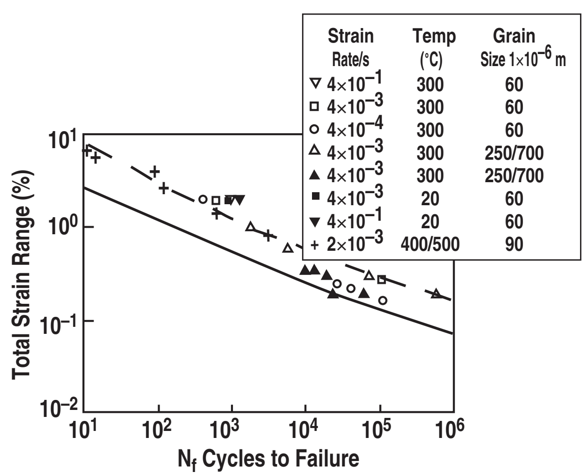

Fig. 3. Fatigue life of annealed OFHC copper in inert environment and plastic strain-range.

TABLE I. Comparison of GA Results With CPI for Stationary Heat Flux

	CPI	GA
Peak temperature (°C)	221	220
Maximum stress (MPa)	34.3	32.9
Maximum strain (%)	0.38	0.36

For the strain calculated for this heat flux (0.36%), the life of the collector will be about 4×10^4 cycles, if:

1. There is no azimuthal non-uniformity of power on the collector walls and
2. There is no degradation of heat transfer at the coolant channels due to fouling (deposition of impurities on the coolant surface).

In practice, both these events could happen, and thermal mapping of the collectors of several gyrotrons has shown about 30% non-uniformity, reducing the life of the collector to less than 4×10^4 thermal cycles. Literature shows that the fouling thermal resistance (R_f) for the flow conditions is $2°\text{C-cm}^2/\text{W}$ [6]. The magnitude of the calculated heat transfer coefficient (η_o) is ~4.7 $\text{W}/\text{cm}^2/°\text{C}$. The effect of fouling on the equivalent heat transfer coefficient (η_e) can be calculated by:

$$\eta_e = (R_f + 1/\eta_o)^{-1} = 0.45 \ \text{W}/°\text{C}/\text{cm}^2 \quad .$$

Thus, in an extreme case, the heat transfer coefficient could degrade to 10% of the clean surface value due to fouling. Figure 4 shows how the strain increases and hence the life of the collector can reduce if the heat transfer coefficient is degraded due to fouling. Fortunately, the degradation of the cooling efficiency can be detected by measuring the outside wall temperature of the collector (Fig. 5) and corrective action, such as acid cleaning the flow channels, taken.

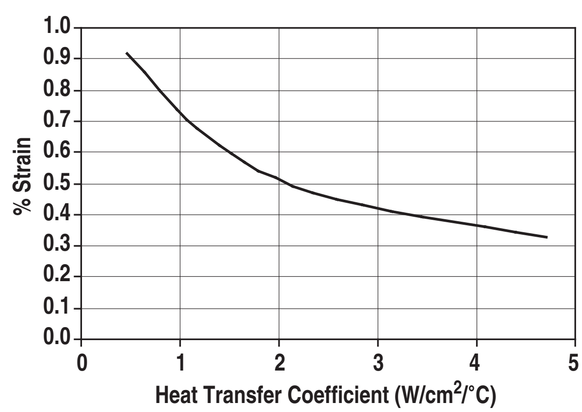

Fig. 4. Increase in strain if heat transfer coefficient is reduced.

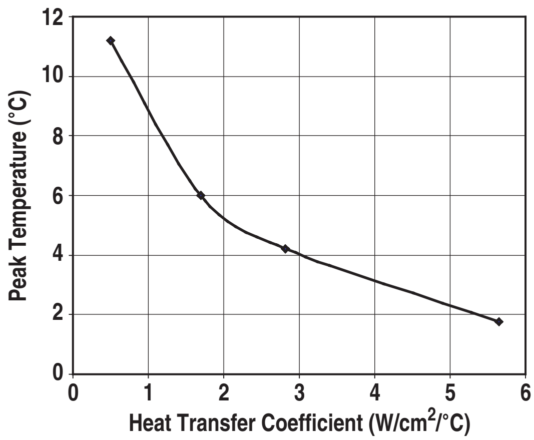

Fig. 5. Effect of heat transfer coefficient on temperature of outer collector wall (1.5 MW power into collector for 1.85 s, 380 GPM flow.

The averaged heat flux can be reduced by sweeping the electron beam over the collector surface (Fig. 6). In this case the sweeping is at a frequency of 4 Hz. This has reduced the maximum time averaged heat flux to ~700 W/cm^2 from a stationary peak of 2100 W/cm^2. It is important to note that, although the time averaged heat flux is substantially reduced due to sweeping, the peak heat flux still is ~2100 $W/cm^2/C$, but sweeping reduces the local temperature increase and therefore reduces the strain. Figure 7 shows a typical temperature response at the location of maximum temperature with sweeping. During sweeping the temperature, stress and strain at each point are oscillating during each sweep cycle. For short pulses, $\lesssim 2$ s in length, the number of fatigue cycles is equal to the number of pulses. For longer pulses approaching equilibrium conditions, the number of fatigue cycles is equal to the pulse length times the sweep frequency. The maximum strain for this condition is ~0.21%. According to fatigue data shown in Fig. 3, this corresponds to a fatigue life of about 5×10^5 cycles. At a frequency of 4 Hz and 10 s pulse length, the fatigue life is equal to 12,500 pulses. This can be compared to life of the collector without sweeping. Without sweeping, the peak heat flux is 2400 $W/cm^2/C$ at one location and the maximum strain is ~0.85%. According to Fig. 3, the life will be about 2,000 pulses. Thus sweeping increases the life of the collector from 2,000 to 12,500 10 s pulses yet does not achieve the target life of 10^5 pulses.

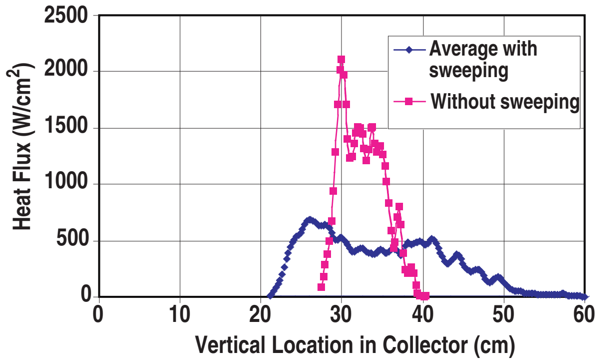

Fig. 6. Effect of sweeping on effective heat flux.

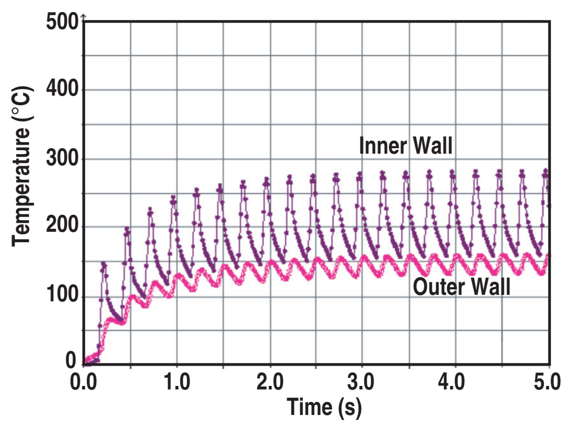

Fig. 7. Typical transient temperature response due to sweeping.

A number of operational, design and material alternatives are possible to increase the lifetime:

1. Sweeping at higher frequency will result in smaller dwell time of peak fluxes at each location and hence will reduce the temperature rise and maximum strains. For example, doubling the frequency will reduce the strain by more than a factor two (reduced temperature level and reduced ΔT) and increase the allowable fatigue cycles by an order of magnitude. However, increased frequency increases the sweep cycles by a factor of two and hence total allowable heat load cycles will increase by a factor of five only. Also, it may not be physically possible to achieve higher sweep frequency owing to magnetic flux penetration limitations.

2. The peak heat flux reduction could be achieved by increasing the diameter and length of the collector and spreading the heat over a larger area by sweeping with an increased amplitude.

3. The temperature level can be reduced and hence the fatigue life can be increased by enhancing the heat transfer coefficient in the coolant channels by roughening or using the swirl tape insert.

4. The temperature difference between the surface and the coolant channel can be reduced by reducing the thickness of the wall of the collector.

Another solution is to change the material of the collector from OFHC copper to dispersion strengthened copper (DSC) such as Glidcop [7]. Although thermal conductivity of DSC is about 80% that of OFHC, DSC maintains its strength at high temperatures and has a high fatigue life even at elevated temperatures. This change is estimated to double the fatigue life for fixed operational scenarios, but the high cost of such large pieces of DSC becomes a potential limiting factor.

III CONCLUSION

1. The failures of gyrotron collectors in the DIII-D installation occurred due to fatigue and high strains associated with the heat loading applied to the OFHC copper.

2. Non-uniform heat flux and degradation of heat transfer coefficient due to fouling can exacerbate the problem. Monitoring the outside wall temperature of the collector to detect this and prevent ensuing damage can be implemented.

3. The life of the collector is increased significantly by sweeping at 4 Hz compared with not sweeping. The lifetime could be increased further by sweeping at a higher frequency and higher amplitude, but this could require modification of the collector design. An increase in collector diameter would also increase the life by reducing the heat flux values. Reducing the wall thickness will reduce the strain and increase life, but cannot be done without consideration of collector strength.

4. Dispersion strengthened copper, which has better fatigue properties than OFHC, could be used.

REFERENCES

[1] COSMOS, A Finite Element Analysis Code, Structural Research, Santa Monica, California, USA.

[2] Kevin Felch, "Collector Fatigue Analysis," General Atomics private communication, October, 2005.

[3] E. Chin and E.E. Reis, "Elastic Plastic Creep Analysis of Brazed CC/OFHC Diverter Tiles," Proc. 16th IEEE/NPSS Symposium on Fusion Engineering, San Diego, California (1995) pp. 1287-1290.

[4] E.E. Reis and R.H. Ryder, "Creep-Fatigue Damage in OFHC Coolant Tubes," Proc. of 19th Symposium on Fusion Technology, Lisbon, Portugal, Vol. 1 (1996) p. 319.

[5] C.B. Baxi, "Thermal Hydraulics of Water Cooled Diverters," Fusion Engineering and Design **56-57**, 195 (2001).

[6] A. Bejan and A. Kraus, *Heat Transfer Handbook*, John Wiley & Sons, Hoboken, New Jersey (2003).

[7] SCM Metal Products, Inc., Research Triangle Park, North Carolina, USA.

Acknowledgments

Work supported by the U.S. Department of Energy under DE-FC02-04ER54698. The authors acknowledge E.E. Reis for providing help to generate the FE model.